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Front-side Metalization By Means Of Flexographic Printing

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Abstract

Flexographic printing is a high-throughput technology which is capable of fine-line printing. The use of a soft and flexible printing plate keeps mechanical stress to silicon wafers during printing low. It is therefore very interesting for the industrial-scale production of seed layers for front-side contact grids on solar cells. Within this work, flexographic printing is applied to silicon solar cells for the first time. We investigate the effect of printing parameters and printing press components on finger width. An average finger width after contact firing of about 44 µm was achieved on wafers of the format 22x60 mm². Due to reduced shading losses compared to screen printed cells the best flexographically printed cells reached an efficiency gain of 0.7%abs. The highest efficiency was 18.1% and was observed on Cz silicon.

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Keywords: flexography; front-side; metalization; printing

1. Introduction

The most common industrial process for producing solar cells features screen-printed contacts. Therefore, contact finger geometry (for example line width) as well as production line output is often limited by screen printing processes. Flexographic printing is capable of tackling both problems simultaneously, as it is a high-throughput technology capable of fine-line printing. So far, finger widths of less than 80µm have been achieved using flexography on ITO substrates [1] [2]. Vital for mass-production of solar cells is a high throughput rate of the technologies used. Currently, a squeegee velocity of 0.2 m/s is common in screen printing for solar cell metallization. This is only one third of the flexographic printing velocity which has been applied in this work. Alignment-time and wafer-feeding of the printing press are similar, while flexographic printing presses are considerably wider than screen printing presses and therefore capable of printing several wafers at the same time. Thus, flexographic printing should allow to enhance throughput limits of current production lines, while making high cell efficiencies possible. Hence, this

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paper presents an overview of research and development of front-side metallization using flexographic printing.

2. Flexographic printing

Flexography is a relief printing technology [3]. Elevated elements of the flexible printing plate transfer the ink while low-lying areas do not come into contact with ink and substrate (*FIG.1*). The ink transfer onto the printing plate is made by the anilox roll, a steel cylinder with finely engraved cells on its surface made of chromium or ceramics. Size and spatial frequency of these cells determine the volume of ink which is transferred and are therefore primarily responsible for the printing quality (*FIG.2*). The cell-volume per unit area is referred to as dip volume, usually denoted in ml/m², while the number of cells per unit length is termed screen ruling and given in L/cm.

Typically, inks for flexographic printing have a relatively low viscosity between 50 mPas and 500 mPas. The printing pressure is usually very low ("kiss printing"), making flexography an applicable technology for printing on rough-textured and breakable surfaces.

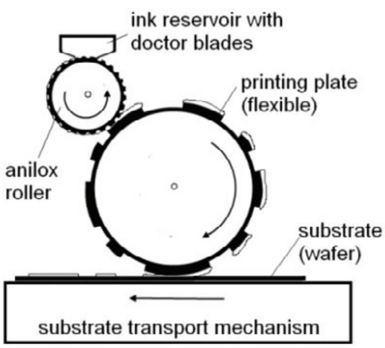

FIG.1: Flexographic printing: by rotation of the anilox roller ink is transferred to elevated elements on the printing plate and from there to the substrate.

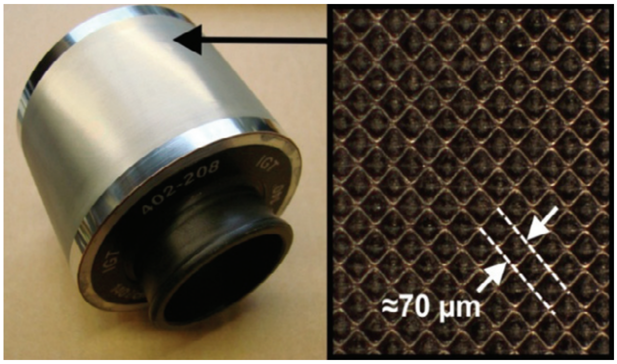

FIG.2: Anilox roll and details of engraved cells (screen ruling 140 L/cm, corresponding to a cell size of ca. 70 µm, dip volume 8.5 ml/m²)

3. Experimental

3.1. Printing technology

A flexographic printing press of type IGT-F1 was used with a diluted screen printing paste ("ink 4"). The non-modified screen printing paste ("ink 5") was used in a standard screen printing process for comparison. In addition, an aerosol jet printing fluid ("ink 1") was available for flexographic printing. All adjustable parameters (printing force, printing speed, anilox force, number of revolutions for ink transfer to the printing plate) have been varied and plotted against line width of the printed contact fingers. Multiple anilox rolls were tested in order to investigate the influence of dip volume and screen ruling on contact finger width. Various printing plate materials with different Shore-hardness have been tested, with those enabling the finest fingers selected for solar cell processing.

The effect of heating the substrate and the inking system prior to the printing process was examined. Due to the low heat capacity of silicon wafers, the substrates were heated together with parts of the printing machine transport mechanism.

3.2. Solar cell processing

Since layer thickness of a flexographically printed contact is below 3 µm a two-step metallization process needs to be applied. After printing and contact firing, a light induced plating (LIP [4], [5]) process step is necessary. The aim of this step is to thicken the contact in order to increase its conductivity.

Two different flexography-inks were available for cell processing on mc and Cz wafers. Due to the limited roller width of the flexographic printing press, a wafer format of 22x60 mm² was used for all cells (including screen printed reference cells). A layout consisting of one Busbar and 11 contact fingers with a nominal finger width of 15 µm was chosen. The emitter sheet resistance of the silicon material was 70 Ω/sq ± 4 Ω/sq.

5 cells of each of the 4 possible combinations (TABLE 1) have been metalized by flexographic printing followed by LIP. Except for front-side metallization only industrial standard process steps were applied. For comparison with processes applied to standard industrial cells, another 5 cells were produced by means of screen printing on mc and Cz silicon.

4. Results

4.1. Printing results

We investigated the contact finger width as a function of contact pressure between printing plate and substrate. *FIG 3* shows that finger width is proportional to printing force.

The influence of anilox roller properties were investigated. High screen ruling of the anilox roller reduces finger width while high dip volume increases finger width. These findings can be derived from *FIG 4* when certain pairs of anilox rollers are compared. AR1 and AR2 have identical dip volume, but different screen ruling, indicating that increasing screen ruling reduces finger width. AR4 and AR5 have identical screen ruling, but different dip volume, indicating that reducing dip volume reduces finger width. However, dip volume cannot be reduced without limit because the amount of ink transferred to the substrate needs to be sufficient to produce contact fingers with minimized number and density of interruptions. No defects were observed for dip volumes of 8.5 ml/m² and above, while at 4.5 ml/m² frequent defects of a maximum diameter of 10 µm occurred, which were filled during the following LIP process step.

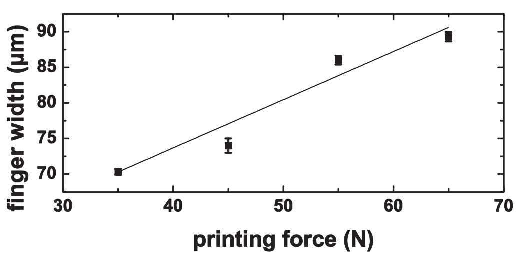

FIG 3: finger width over printing force

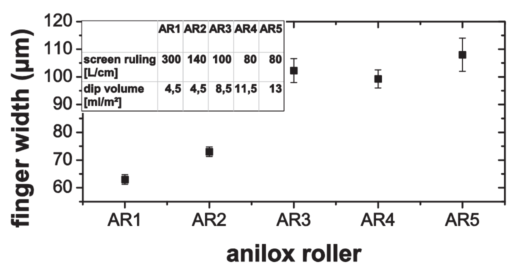

FIG 4: finger width over anilox roller

Printing force, printing speed, anilox force and number of revolutions for ink transfer to the printing plate showed only weak influence on finger width. This holds also true for a variation of the printing velocity, which showed no influence on finger width between 0.5 m/s and 1.5 m/s, suggesting that a threefold increase of throughput is possible without loss in print quality.

Layer thickness of flexographically printed seed layers was estimated at 2-3 µm according to SEM images of finger sections (*FIG.6*). The average finger width of all samples processed was 44 µm, while some material combinations resulted in considerably lower finger widths (TABLE I). The lowest finger width observed was 32 µm (*FIG.5*) on textured Cz silicon.

After LIP, the lowest observed finger width was 57 µm, while the average finger width of all samples processed was 67 µm. This constitutes a considerable improvement compared to screen printing technology, which yielded an average finger width of 100µm.

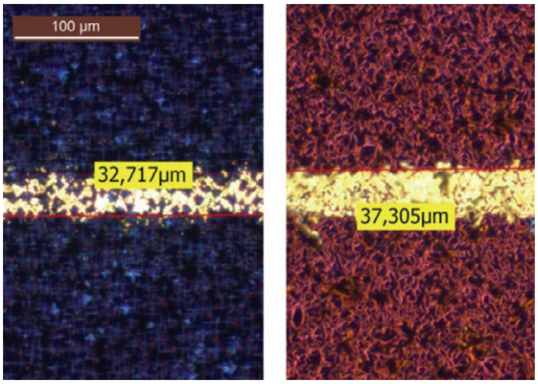

FIG.5: finest flexographically printed contact fingers on textured Cz (left) and mc (right) silicon before LIP

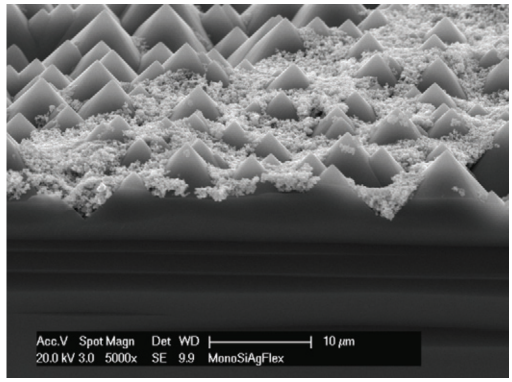

FIG.6: SEM image of a contact finger (section view) before LIP (Ink 1 on textured Cz silicon)

TABLE I: average finger width (FW) of 3 printed contact fingers before and after LIP

process	**Flexography before LIP**				**Flexography after LIP**				**Screen printing**	
Ink	Ink 1		Ink 4		Ink 1		Ink 4		Ink 5	
Si-Material	Cz	mc	Cz	mc	Cz	mc	Cz	mc	Cz	mc
Finger width/µm	47±1	45±4	37±3	45±3	71±1	71±1	57±1	69±5	102±2	98±2

Heating of substrate and inking system led to substantially more homogenous contacts (FIG.7). This is mainly the result of an increased amount of transferred ink, which was observed in both cases. Heating the substrate to 100°C prior to the printing process increased the amount of transferred ink by 107% compared to printing on a substrate at room temperature. Heating the inking system (anilox roller, doctor blade, printing plate cylinder) to 55°C increased the ink transfer by 51%.

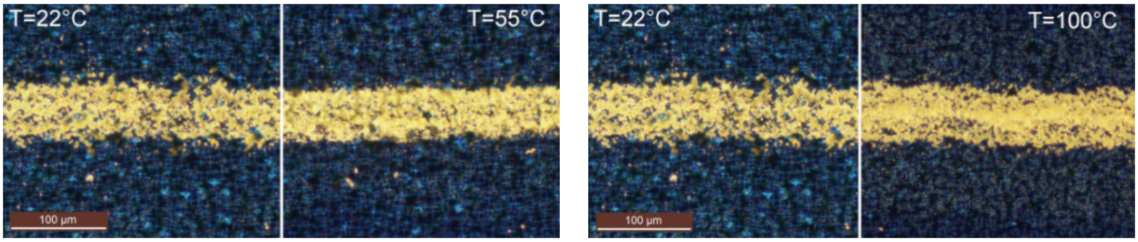

FIG.7: printing results for heated inking unit (left) and heated substrate (right)

4.2. Solar cell results

Due to yield losses during wafer handling in production it was not possible to carry out IV-measurements of one solar cell of each material combination. From the available curves, all IV parameters were derived. *FIG.8* shows best values of the efficiency results for flexographically printed cells and screen printed reference cells, plotted against firing temperature. The measurement error is $\pm 3\%_{rel}$.

The highest efficiency achieved with flexography on Cz silicon was 18.1%, while on mc silicon 16.5% were achieved. A comparison of the best flexographic cells with screen printed reference cells was carried out. An efficiency gain of $+0.7\%_{abs}$ was observed on Cz silicon, while on mc silicon the efficiency gain amounted to $+0.6\%_{abs}$. Three components contribute to this result: j_{sc} of the flexographically printed cells was increased by about 1% due to the reduction of shaded area by about 1% of the total cell area. Probably recombination losses under the contact were reduced by choosing a seed-and-plate production process [5]. FF of the flexographically printed cells were improved by low contact resistivities (*TABLE II*) and possibly high contact finger conductivity, which is typical for seed-and-plate contact fingers.

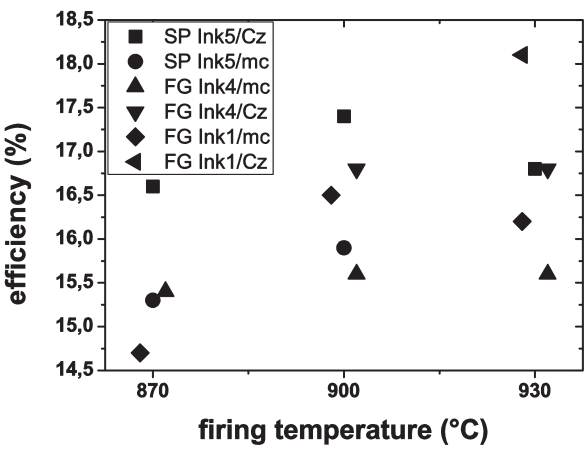

FIG.8: Efficiencies of flexographically printed cells (FG) and screen printed reference cells (SP) vs. firing temperature. The measurement error is $\pm 3\%_{rel}$.

The contact resistivity was measured after firing the cells at 900°C and LIP. It was obtained using a TLM setup. The results (*TABLE II*) show generally low values compared to screen printed contacts, which usually have contact resistivities of approximately 5 mΩcm².

TABLE II: contact resistivity for different material combinations for flexographically printed solar cells after LIP

material combination	**Ink 1/Cz**	**Ink 1/mc**	**Ink 4/Cz**	**Ink 4/mc**
contact resistivity ρ_c / mΩcm²	0.7±0.1	1.8±0.2	2.3±0.9	2.2±0.2

5. Conclusion

Flexographic printing is a promising approach to mass-production of seed layers for front-side metallization. The most important printing parameters are screen ruling of the anilox roller and printing force. Heating of the substrate and the inking system increased finger homogenity. An average finger width of 44 µm before LIP and 67 µm after LIP was achieved on textured silicon.

Compared to screen printed reference cells an efficiency gain of up to +0.7%$_{abs}$ was observed. This is the result of reduced shading losses as well as very low contact resistivity and positive effects from the chosen seed-and-plate production process. A variation of the firing temperature was carried out and the highest efficiencies achieved were 16.5% on mc silicon and 18.1% on Cz silicon.

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